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Introduction to MPI

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Outline

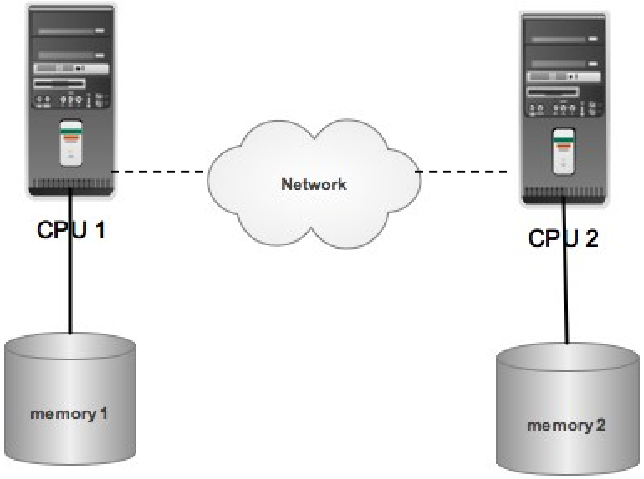
- Overview
- Basics
  - Hello World in MPI
  - Compiling and running MPI programs
- MPI Messages
- MPI Communicators
- Point-to-point communication
- Collective communication
- Releases
- MPI references and documentation

Introduction

- What is MPI? Message Passing Interface
- What is message passing?
  - Sending and receiving messages between tasks or processes
  - Can include performing operations on data in transit and synchronizing tasks
- Why send messages?
  - Clusters have distributed memory, i.e. each process has its own address space and no way to get at another's
- How do you send messages?
  - Programmer makes use of an Application Programming *Interface* (API) that specifies the functionality of high-level communication routines
  - Functions give access to a low-level *implementation* that takes care of sockets, buffering, data copying, message routing, etc.

Overview | API for distributed memory parallelism

- Assumption: processes do not see each other's memory
- Communication speed is determined by some kind of network
  - Typical network = switch + cables + adapters + software stack…
- Key: the implementation of a message passing API (like MPI) can be optimized for any given network
  - Program gets the benefit
  - No code changes required
  - Works in shared memory, too



Overview | Why use MPI?

- MPI is a de facto standard
  - Public domain versions are easy to install
  - Vendor-optimized version are available on most hardware
- MPI is “tried and true”
  - MPI-1 was released in 1994, MPI-2 in 1996
- MPI applications can be fairly portable
- MPI is a good way to learn parallel programming
- MPI is expressive: it can be used for many different models of computation, therefore can be used with many different applications
- MPI code is efficient (though some think of it as the “assembly language of parallel processing”)

Basics

The basic outline of an MPI program follows these general steps:

- *Include the MPI header file --*
  #include <mpi.h> for basic definitions and types, implementation-specific.
- *Initialize communications --*
  MPI_INIT initializes the MPI environment
  MPI_COMM_SIZE returns the number of processes
  MPI_COMM_RANK returns this process's number (rank)
- *Communicate to share data between processes --*
  MPI_SEND sends a message
  MPI_RECV receives a message
- *Exit from the message-passing system --*
  MPI_FINALIZE

Basics | Minimal Code Example

```
#include <. . . .>
#include "mpi.h"
main(int argc, char **argv)
{
   char message[20];
   int i, rank, size, type = 99;
   MPI_Status status;
   MPI_Init(&argc, &argv);
   MPI_Comm_size(MPI_COMM_WORLD, &size);
   MPI_Comm_rank(MPI_COMM_WORLD, &rank);
   if (rank == 0) {
      strcpy(message, "Hello, world");
      for (i = 1; i < size; i++)
         MPI_Send(message, 13, MPI_CHAR, i, type, MPI_COMM_WORLD);
   }
   else
      MPI_Recv(message, 20, MPI_CHAR, 0, type, MPI_COMM_WORLD, &status);
   printf( "Message from process = %d : %.13s\n", rank,message);
   MPI_Finalize();
}
```

Basics — Initialize and Close Environment

- #include <. . . .>
- #include "mpi.h"
- main(int argc, char **argv)
- {
- char message[20];
- int i, rank, size, type = 99;
- MPI_Status status;
- MPI_Init(&argc, &argv);
- MPI_Comm_size(MPI_COMM_WORLD, &size);
- MPI_Comm_rank(MPI_COMM_WORLD, &rank);
- if (rank == 0) {
- strcpy(message, "Hello, world");
- for (i = 1; i < size; i++)
- MPI_Send(message, 13, MPI_CHAR, i, type, MPI_COMM_WORLD);
- }
- else
- MPI_Recv(message, 20, MPI_CHAR, 0, type, MPI_COMM_WORLD, &status);
- printf("Message from process = %d : %.13s\n", rank,message);
- MPI_Finalize();
- }

Initialize MPI environment

An implementation may also use this call as a mechanism for making the usual argc and argv command-line arguments from “main” available to all tasks (C language only).

Close MPI environment

Basics

Query Environment

```
#include <. . . .>
#include "mpi.h"
main(int argc, char **argv)
{
  char message[20];
  int i, rank, size, type = 99;
  MPI_Status status;
  MPI_Init(&argc, &argv);
  MPI_Comm_size(MPI_COMM_WORLD, &size);
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);
  if (rank == 0) {
    strcpy(message, "Hello, world");
    for (i = 1; i < size; i++)
      MPI_Send(message, 13, MPI_CHAR, i, type, MPI_COMM_WORLD);
  }
  else
    MPI_Recv(message, 20, MPI_CHA ... D, &status);
  printf( "Message from process = %d : ... );
  MPI_Finalize();
}
```

Returns number of Processes
This, like nearly all other MPI functions, must be called after MPI_Init and before MPI_Finalize. Input is the name of a communicator (MPI_COMM_WORLD is the default communicator) and output is the size of that communicator.

Returns this process' number, or rank
Input is again the name of a communicator and the output is the rank of this process in that communicator.

Basics | Pass Messages

```
#include <. . . .>
#include "mpi.h"
main(int argc, char **argv)
{
   char message[20];
   int i, rank, size, type = 99;
   MPI_Status status;
   MPI_Init(&argc, &argv);
   MPI_Comm_size(MPI_COMM_WORLD, &size);
   MPI_Comm_rank(MPI_COMM_WORLD, &rank);
   if (rank == 0) {
      strcpy(message, "Hello, world");
      for (i = 1; i < size; i++)
         MPI_Send(message, 13, MPI_CHAR, i, type, MPI_COMM_WORLD);
   }
   else
      MPI_Recv(message, 20, MPI_CHAR, 0, type, MPI_COMM_WORLD, &status);
   printf( "Message from process = %d : %.13s\n", rank,message);
   MPI_Finalize();
}
```

Send a message
Blocking send of data in the buffer.

Receive a message
Blocking receive of data into the buffer.

Basics | Compiling MPI programs

- Generally use a special compiler or compiler wrapper script
  - Not defined by the standard
  - Consult your implementation
  - Correctly handles include path, library path, and libraries
- MPICH-style (the most common)

  `mpicc -o foo foo.c`

  `mpif90 -o foo foo.f` (also mpif77)
- Some MPI specific compiler options

  `-mpilog` -- Generate log files of MPI calls

  `-mpitrace` -- Trace execution of MPI calls

  `-mpianim` -- Real-time animation of MPI (not available on all systems)
- Note: compiler/linker names are specific to MPICH. On IBM Power systems, they are *mpcc_r* and *mpxlf_r* respectively

Basics | Running MPI programs

- To run a simple MPI program using MPICH

  ```
  mpirun -np 2 ./foo
  mpiexec -np 2 ./foo
  ```

- Some MPI specific running options

  `-t` -- shows the commands that *mpirun* would execute

  `-help` -- shows all options for *mpirun*

- To run over Ranger's InfiniBand (as part of an SGE script)

  ```
  ibrun ./foo
  ```

  – The scheduler handles the rest

- Note: *mpirun* and *mpiexec* are not part of MPI, but a similar command can be found in nearly all implementations
  – There are exceptions: on the IBM SP, for example, it is *poe*

Messages — 3 Parameters Describe the Data

MPI_Send(message, 13, MPI_CHAR, i, type, MPI_COMM_WORLD);

MPI_Recv(message, 20, MPI_CHAR, 0, type, MPI_COMM_WORLD, &status);

Type of data, should be same for send and receive
MPI_Datatype type

Number of elements (items, not bytes)
Recv number should be greater than or equal to amount sent
int count

Address where the data start
void data*

Messages — 3 Parameters Specify Routing

```
MPI_Send(  message, 13, MPI_CHAR,  i,  type, MPI_COMM_WORLD  );

MPI_Recv(  message, 20, MPI_CHAR,  0, type, MPI_COMM_WORLD, &status);
```

Identify process you're communicating with by rank number
int dest/src

Arbitrary tag number, must match up (receiver can specify MPI_ANY_TAG to indicate that any tag is acceptable)
int tag

Communicator specified for send and receive must match, no wildcards
MPI_Comm comm

Returns information on received message
MPI_Status status*

Messages | Fortran Notes

```
mpi_send (data, count, type, dest, tag, comm, ierr)
mpi_recv (data, count, type, src,  tag, comm, status, ierr)
```

- A few Fortran particulars
  - All Fortran arguments are passed by reference
  - *INTEGER ierr:* variable to store the error code (in C/C++ this is the return value of the function call)
- Wildcards are allowed
  - *src* can be the wildcard MPI_ANY_SOURCE
  - *tag* can be the wildcard MPI_ANY_TAG
  - *status* returns information on the source and tag, useful in conjunction with the above wildcards (receiving only)

MPI_COMM | MPI Communicators

- Communicators
  - Collections of processes that can communicate with each other
  - Most MPI routines require a communicator as an argument
  - Predefined communicator MPI_COMM_WORLD encompasses all tasks
  - New communicators can be defined; any number can co-exist
- Each communicator must be able to answer two questions
  - *How many processes exist in this communicator?*
  - MPI_Comm_size returns the answer, say, N_p
  - *Of these processes, which process (numerical rank) am I?*
  - MPI_Comm_rank returns the rank of the current process within the communicator, an integer between 0 and N_p-1 inclusive
  - Typically these functions are called just after MPI_Init

MPI_COMM C Example

```
#include <mpi.h>
main(int argc, char **argv){
   int np, mype, ierr;

   ierr = MPI_Init(&argc, &argv);
   ierr = MPI_Comm_size(MPI_COMM_WORLD, &np);
   ierr = MPI_Comm_rank(MPI_COMM_WORLD, &mype);
            :
   MPI_Finalize();
}
```

MPI_COMM C++ Example

```
#include “mpif.h”
[other includes]
int main(int argc, char *argv[]){
   int np,  mype,  ierr;
 [other declarations]
            :
          MPI::Init(argc, argv);
   np   = MPI::COMM_WORLD.Get_size();
   mype = MPI::COMM_WORLD.Get_rank();
            :
        [actual work goes here]
            :
          MPI::Finalize();
}
```

MPI_COMM Fortran Example

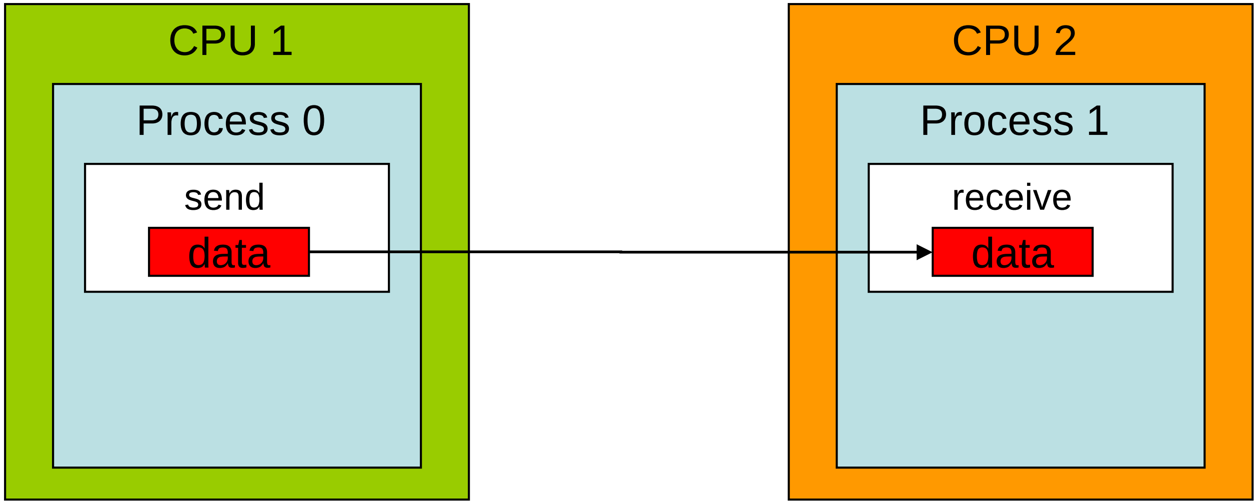
```
program param
  include ‘mpif.h’
  integer ierr, np, mype

  call mpi_init(ierr)
  call mpi_comm_size(MPI_COMM_WORLD, np  , ierr)
  call mpi_comm_rank(MPI_COMM_WORLD, mype, ierr)
           :
  call mpi_finalize(ierr)
end program
```

Point to Point Topics

- MPI_SEND and MPI_RECV
- Synchronous vs. buffered (asynchronous) communication
- Blocking send and receive
- Non-blocking send and receive
- Combined send/receive
- Deadlock, and how to avoid it

Point to Point Send and Recv: Simple

- Sending data ***from*** one point (process/task)
  to another point (process/task)
- One task sends while another receives



Point to Point | Send and Recv: So many choices

The communication mode indicates how the message should be sent.

Communication Mode	Blocking Routines	Non-Blocking Routines
Synchronous	MPI_Ssend	MPI_Issend
Ready	MPI_Rsend	MPI_Irsend
Buffered	MPI_Bsend	MPI_Ibsend
Standard	MPI_Send	MPI_Isend
	MPI_Recv	MPI_Irecv
	MPI_Sendrecv	
	MPI_Sendrecv_replace	

Note: the receive routine does not specify the communication mode -- it is simply blocking or non-blocking.

Point to Point Blocking vs Non-Blocking

A ***blocking*** send or receive call suspends execution of the process until the message buffer being sent/received is safe to use.

A ***non-blocking*** call initiates the communication process; the status of data transfer and the success of the communication must be verified independently by the programmer.

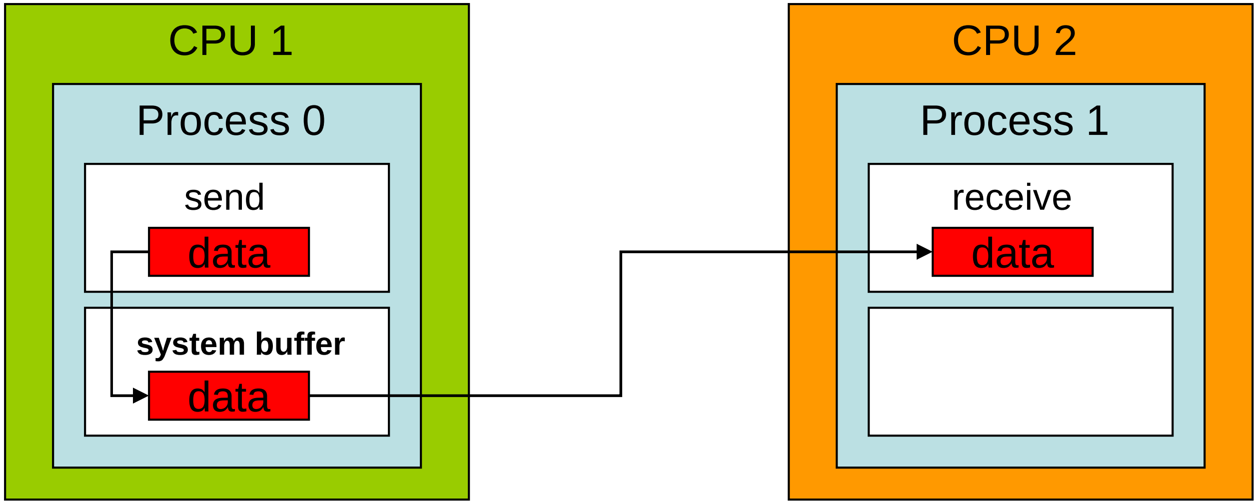
Point to Point Communication Modes

Mode	Pros	Cons
Synchronous – sending and receiving tasks must ‘handshake’.	- Safest, therefore most portable - No need for extra buffer space - SEND/RECV order not critical	Synchronization overhead
Ready- assumes that a ‘ready to receive’ message has already been received.	- Lowest total overhead - No need for extra buffer space - Handshake not required	RECV *must* precede SEND
Buffered – move data to a buffer so process does not wait.	- Decouples SEND from RECV - no sync overhead on SEND - Programmer controls buffer size	Buffer copy overhead
Standard – defined by the implementer; meant to take advantage of the local system.	- Good for many cases - Compromise position	Your program may not be suitable

Point to Point Overhead

- **System overhead**
  cost of transferring data from the sender's message buffer onto the network, then from the network into the receiver's message buffer.
- **Synchronization overhead**
  time spent waiting for an event to occur on another task, e.g. waiting for a receive to be executed and for the handshake to arrive before the message can be transferred.
- **MPI_Send():** A blocking call which returns only when data has been sent from its buffer
- **MPI_Recv():** A blocking receive which returns only when data has been received onto its buffer
- Generally speaking, MPI communications operate in the “rendezvous protocol”, which involves a handshake procedure in order to establish communication.

Point to Point Buffered send, MPI_Bsend



- Message contents are sent to a system-controlled block of memory
- Process 0 continues executing other tasks; when process 1 is ready to receive, the system simply copies the message from the system buffer into the appropriate memory location controlled by process
- Must be preceded with a call to MPI_Buffer_attach

Point to Point MPI_Sendrecv

```
MPI_Sendrecv(sendbuf, sendcount, sendtype, dest,
sendtag, recvbuf, recvcount, recvtype, source, recvtag,
comm, status)
```

- Useful for communication patterns where each of a pair of nodes both sends and receives a message (two-way communication).
- Executes a blocking send and a blocking receive operation
- Both operations use the same communicator, but have distinct tag arguments

Point to Point | One-way blocking/non-blocking

- Blocking send, non-blocking recv

```
IF (rank==0) THEN
   CALL MPI_SEND(sendbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,ie)
ELSEIF (rank==1) THEN
   CALL MPI_IRECV(recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,req,ie)
   CALL MPI_WAIT(req,status,ie)
ENDIF
```

- Non-blocking send, non-blocking recv

```
IF (rank==0) THEN
   CALL MPI_ISEND(sendbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,req,ie)
ELSEIF (rank==1) THEN
   CALL MPI_IRECV(recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,req,ie)
ENDIF
CALL MPI_WAIT(req,status,ie)
```

Point to Point Two-way communication: deadlock!

- **Deadlock 1**

```
IF (rank==0) THEN
   CALL MPI_RECV(recvbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,status,ie)
   CALL MPI_SEND(sendbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,ie)
ELSEIF (rank==1) THEN
   CALL MPI_RECV(recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,status,ie)
   CALL MPI_SEND(sendbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,ie)
ENDIF
```

- **Deadlock 2**

```
IF (rank==0) THEN
   CALL MPI_SEND(sendbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,ie)
   CALL MPI_RECV(recvbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,status,ie)
ELSEIF (rank==1) THEN
   CALL MPI_SEND(sendbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,ie)
   CALL MPI_RECV(recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,status,ie)
ENDIF
```

Point to Point Two-way communication: solutions

- Solution 1

```
IF (rank==0) THEN
   CALL MPI_SEND(sendbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,ie)
   CALL MPI_RECV(recvbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,status,ie)
ELSEIF (rank==1) THEN
   CALL MPI_RECV(recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,status,ie)
   CALL MPI_SEND(sendbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,ie)
ENDIF
```

- Solution 2

```
IF (rank==0) THEN
   CALL MPI_SENDRECV(sendbuf,count,MPI_REAL,1,tag, &
                recvbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,status,ie)
ELSEIF (rank==1) THEN
   CALL MPI_SENDRECV(sendbuf,count,MPI_REAL,0,tag, &
                recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,status,ie)
ENDIF
```

Point to Point Solutions (continued)

- Solution 3

```
IF (rank==0) THEN
   CALL MPI_IRECV(recvbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,req,ie)
   CALL MPI_SEND(sendbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,ie)
ELSEIF (rank==1) THEN
   CALL MPI_IRECV(recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,req,ie)
   CALL MPI_SEND(sendbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,ie)
ENDIF
CALL MPI_WAIT(req,status)
```

- Solution 4

```
IF (rank==0) THEN
   CALL MPI_BSEND(sendbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,ie)
   CALL MPI_RECV(recvbuf,count,MPI_REAL,1,tag,MPI_COMM_WORLD,status,ie)
ELSEIF (rank==1) THEN
   CALL MPI_BSEND(sendbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,ie)
   CALL MPI_RECV(recvbuf,count,MPI_REAL,0,tag,MPI_COMM_WORLD,status,ie)
ENDIF
```

Point to Point | Two-way communications: summary

	CPU 0	CPU 1
Deadlock1	Recv/Send	Recv/Send
Deadlock2	Send/Recv	Send/Recv
Solution1	Send/Recv	Recv/Send
Solution2	SendRecv	SendRecv
Solution3	IRecv/Send, Wait	IRecv/Send, Wait
Solution4	BSend/Recv	BSend/Recv

Point to Point C Example

```
#include  "mpi.h"
main(int argc, char **argv){
int ipe, ierr; double a[2];
MPI_Status status;
MPI_Comm icomm = MPI_COMM_WORLD;
ierr = MPI_Init(&argc, &argv);
ierr = MPI_Comm_rank(icomm, &ipe);
ierr = MPI_Comm_size(icomm, &myworld);
if(ipe == 0){
    a[0] = mype; a[1] = mype+1;
    ierr = MPI_Send(a,2,MPI_DOUBLE, 1,9, icomm);
  }
else if (ipe == 1){
    ierr = MPI_Recv(a,2,MPI_DOUBLE, 0,9,icomm,&status);
    printf("PE %d, A array= %f %f\n",mype,a[0],a[1]);
  }
  MPI_Finalize();
}
```

Point to Point Fortran Example

```
program sr
   include "mpif.h"
   real*8,  dimension(2)                  :: A
   integer, dimension(MPI_STATUS_SIZE) :: istat
   icomm = MPI_COMM_WORLD
   call mpi_init(ierr)
   call mpi_comm_rank(icomm,mype,ierr)
   call mpi_comm_size(icomm,np  ,ierr);

   if(mype.eq.0) then
    a(1) = real(ipe); a(2) = real(ipe+1)
    call mpi_send(A,2,MPI_REAL8, 1,9,icomm, ierr)
   else if (mype.eq.1) then
    call mpi_recv(A,2,MPI_REAL8, 0,9,icomm, istat,ierr)
    print*,"PE ",mype,"received A array =",A
   endif

   call mpi_finalize(ierr)
end program
```

Collective Topics

- Overview
- Barriers
- Data Movement Operations
- Reduction Operations

Collective Overview

- What if one processor wants to send to everyone else?

```
if (mytid == 0 ) {
  for (tid=1; tid<ntids; tid++) {
    MPI_Send( (void*)a, /* target= */ tid, … );
  }
} else {
  MPI_Recv( (void*)a, 0, … );
}
```

- Implements a very naive, serial broadcast
- Too primitive
  - leaves no room for the OS / switch to optimize
  - leaves no room for more efficient algorithms
- Too slow: most receive calls will have a long wait for completion

Collective Overview

- Involve ALL processes within a communicator
- There are three basic types of collective communications:
  - Synchronization (MPI_Barrier)
  - Data movement (MPI_Bcast/Scatter/Gather/Allgather/AlltoAll)
  - Collective computation (MPI_Reduce/Allreduce/Scan)
- Programming considerations & restrictions
  - Blocking operation
  - No use of message tag argument
  - Collective operation within subsets of processes require separate grouping and new communicator
  - Can only be used with MPI predefined datatypes

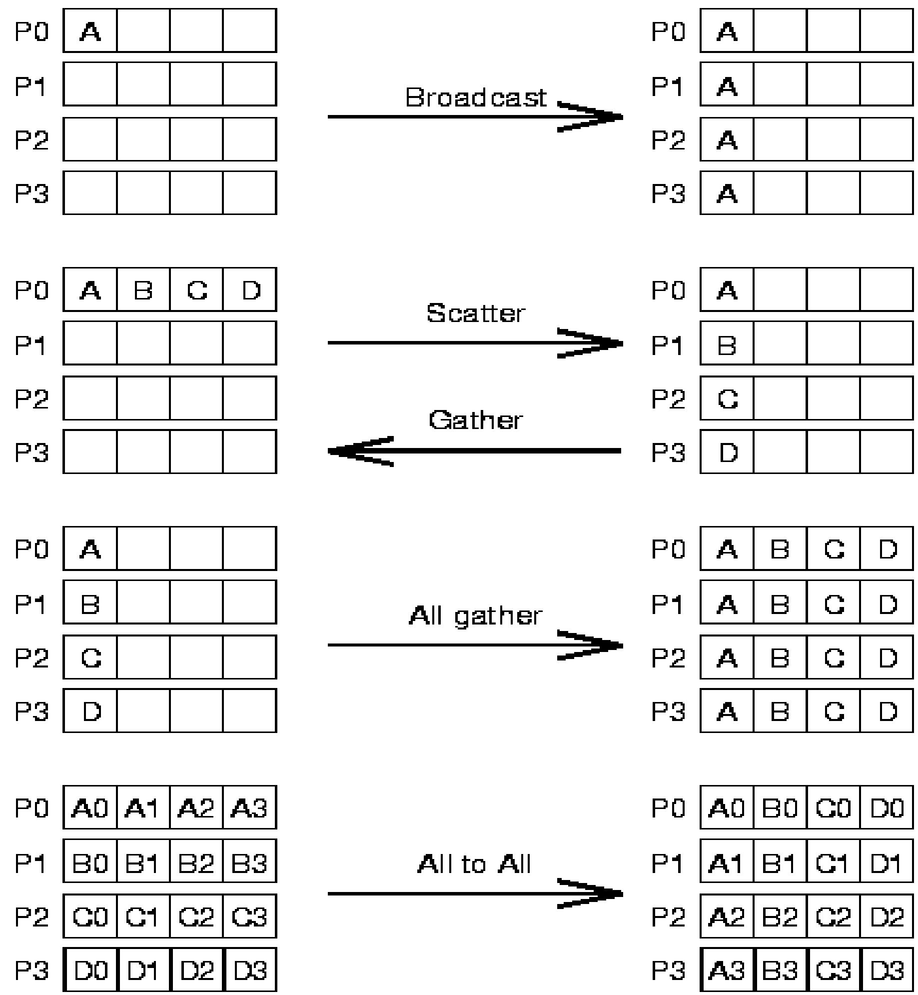
Collective | Barrier synchronization and broadcast

- *Barrier* blocks until all processes in comm have called it
- Useful when measuring communication/computation time
  - **`mpi_barrier(comm, ierr)`**
  - **`MPI_Barrier(comm)`**

- *Broadcast* sends data from root to all processes in comm
  - **`mpi_bcast(data, count, type, root, comm, ierr)`**
  - **`MPI_Bcast(data, count, type, root, comm)`**

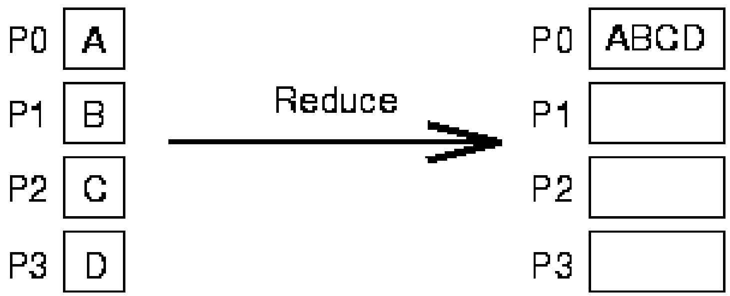
Collective Data movement

- Broadcast
- Scatter
- Gather
- Allgather
- Alltoall

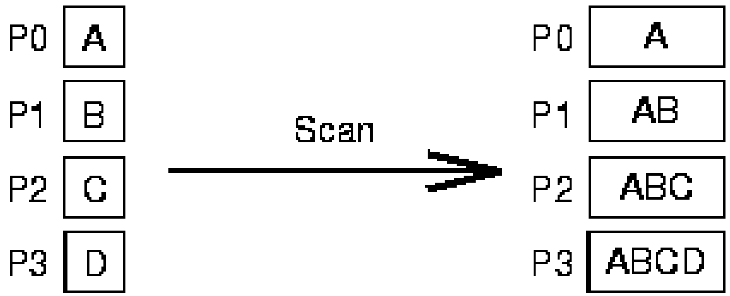


Collective Reduction Operations

- Reduce



- Scan



Collective Reduction Operations

Name	Meaning
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical and
MPI_BAND	Bit-wise and
MPI_LOR	Logical or
MPI_BOR	Bit-wise or
MPI_LXOR	Logical xor
MPI_BXOR	Logical xor
MPI_MAXLOC	Max value and location
MPI_MINLOC	Min value and location

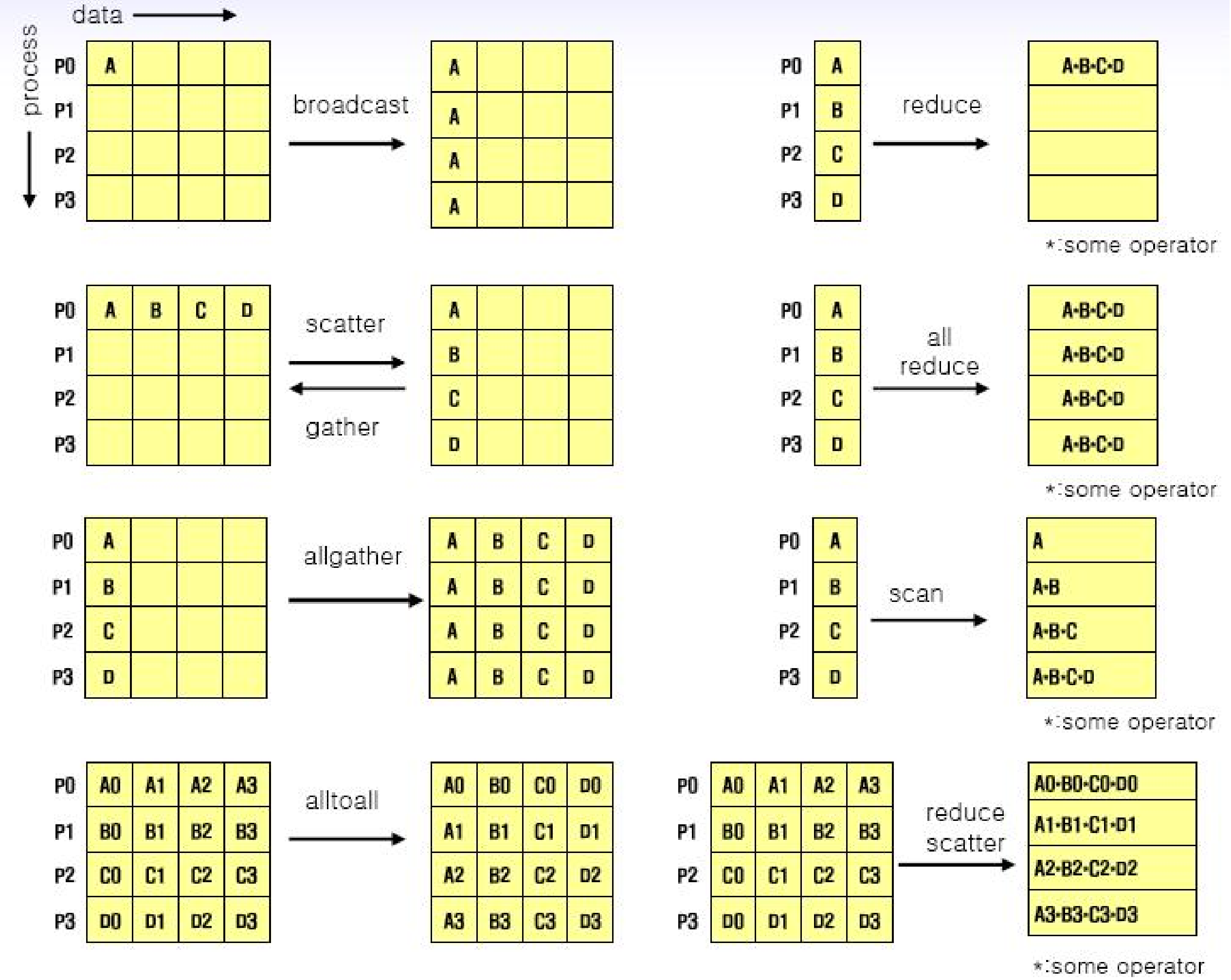
Collective C Example

```
#include <mpi.h>
#define WCOMM MPI_COMM_WORLD
main(int argc, char **argv){
  int npes, mype, ierr;
  double sum, val; int calc, knt=1;
  ierr = MPI_Init(&argc, &argv);
  ierr = MPI_Comm_size(WCOMM, &npes);
  ierr = MPI_Comm_rank(WCOMM, &mype);

  val = (double) mype;

  ierr=MPI_Allreduce(&val,&sum,knt,MPI_DOUBLE,MPI_SUM,WCOMM);

  calc=(npes-1 +npes%2)*(npes/2);
  printf(" PE: %d sum=%5.0f calc=%d\n",mype,sum,calc);
  ierr = MPI_Finalize();
}
```

Collective Fortran Example

```
program sum2all
include 'mpif.h'

  icomm = MPI_COMM_WORLD
  knt = 1
  call mpi_init(ierr)
  call mpi_comm_rank(icomm,mype,ierr)
  call mpi_comm_size(icomm,npes,ierr)
  val = dble(mype)

  call mpi_allreduce(val,sum,knt,MPI_REAL8,MPI_SUM,icomm,ierr)

  ncalc=(npes-1 + mod(npes,2))*(npes/2)
  print*,' pe#, sum, calc. sum = ',mype,sum,ncalc
  call mpi_finalize(ierr)

end program
```

Collective


data
process
P0
P1
P2
P3
A
broadcast
A
A
A
A
reduce
A·B·C·D
*:some operator
A B C D
scatter
gather
all
reduce
allgather
scan
A·B
A·B·C
alltoall
A0 A1 A2 A3
B0 B1 B2 B3
C0 C1 C2 C3
D0 D1 D2 D3
reduce
scatter
A0·B0·C0·D0
A1·B1·C1·D1
A2·B2·C2·D2
A3·B3·C3·D3

MPI-1

- MPI-1 - Message Passing Interface (v. 1.2)
  - Library standard defined by committee of vendors, implementers, and parallel programmers
  - Used to create parallel SPMD codes based on explicit message passing
- Available on almost all parallel machines with C/C++ and Fortran bindings (and occasionally with other bindings)
- About 125 routines, total
  - 6 basic routines
  - The rest include routines of increasing generality and specificity

MPI-2

- Includes features left out of MPI-1
  - One-sided communications
  - Dynamic process control
  - More complicated collectives
  - Parallel I/O (MPI-IO)
- Implementations came along only gradually
  - Not quickly undertaken after the reference document was released (in 1997)
  - Now OpenMPI, MPICH2 (and its descendants), and the vendor implemenations are nearly complete or fully complete
- Most applications still rely on MPI-1, plus maybe MPI-IO

References

- MPI-1 and MPI-2 standards
  - http://www.mpi-forum.org/docs/mpi-11-html/mpi-report.html
  - http://www.mpi-forum.org/docs/mpi-20-html/mpi2-report.htm
  - http://www.mcs.anl.gov/mpi/ (other mirror sites)
- Freely available implementations
  - MPICH, http://www.mcs.anl.gov/mpi/mpich
  - LAM-MPI, http://www.lam-mpi.org/
- Books
  - *Using MPI*, by Gropp, Lusk, and Skjellum
  - *MPI Annotated Reference Manual,* by Marc Snir, *et al*
  - *Parallel Programming with MPI*, by Peter Pacheco
  - *Using MPI-2*, by Gropp, Lusk and Thakur
- Newsgroup: comp.parallel.mpi